Interfacial magnetism of fcc Fe and the effect of the oscillatory interlayer coupling on the Ni magnetic properties in Ni/Fe/Co/Cu(100)

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Ni/Fe/Co/Cu(100) system was studied using photoemission electron microscope. By analyzing element specific domain images, we found that there exists oscillatory interlayer coupling between the Co and Ni layers across the fcc Fe layer. With the thickness and temperature dependent studies, we found strong evidence that the Fe layers at both the Fe/Co and Fe/Ni interfaces are ferromagnetically ordered in the 4–12 ML thickness range, and that the ferromagnetically ordered layer at the Fe/Ni interface disappears as the temperature exceeds the Curie temperature of the Ni layer. Moreover, the oscillatory interlayer coupling between the Co and Ni layers results in an oscillation of the Ni layer Curie temperature.

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I. INTRODUCTION

Metastable phase of face-centered-cubic (fcc) Fe has attracted a great interest in magnetism research, especially after the realization of fcc Fe thin films on Cu(100) substrate.^{1,2} The room-temperature grown fcc Fe film is ferromagnetic below 4 ML, but changes into antiferromagnetic plus a ferromagnetically ordered layer between 5 and 11 ML.^{3,4} These rich magnetic phases indicate that the fcc Fe film on Cu(100) may just be at a magnetic instability point. Band-structure calculation shows⁵ that fcc Fe has two energy minima in the range of 2.3-2.8 a.u. Wigner-Seitz radius $(r_{\rm WS})$. The instability point between these two phases occurs at a $r_{\rm WS}$ of 2.66 a.u. Noting that the Wigner-Seitz radius is 2.652 a.u. for bulk fcc Fe and 2.667 a.u. for Cu, it was speculated that the observed rich magnetic phases in fcc Fe/ Cu(100) must be associated with the structural changes of the fcc Fe film. Indeed, structural analysis using low-energy electron diffraction (LEED) and scanning tunneling microscopy shows characteristic surface reconstruction, interlayer spacing, and local atomic distortion in different magnetic phases.^{6,7} In particular, the ferromagnetic phase below 4 ML and the ferromagnetic surface ferromagnetically ordered layer in the 5-11 ML range were identified to have a greater interlayer spacing than the antiferromagnetic phase⁶ where a spin density wave may have been developed.8 Theoretical calculations, allowing structural relaxations, were also developed accordingly to explain the observed magnetic phases of the fcc Fe films. 9,10

To further clarify the structural and magnetic correlation, experimental efforts have been made to grow Fe film on Cu(100) with different method, 11 on substrates with different lattice constants, 12,13 and on ferromagnetic fcc Co(100) or Ni(100) that were epitaxially grown on Cu(100). 14 In the latter case, the fcc Fe should have similar structural properties as on Cu(100) but different electronic interfacial properties. It was found that the Fe/Co(100) system exhibits a mag-

netic behavior similar to the Fe/Cu(100) system despite a higher magnetic Curie temperature (T_C) . ¹⁵ This result shows that the primary determining factor for the magnetic phase of fcc Fe film is its lattice structure rather than its interfacial electronic property. There is, however, a major difference between the Fe/Cu(100) and Fe/Co(100) systems at the location of the ferromagnetically ordered layer in the 5-12 ML thickness range. Oxygen absorption experiments 14,15 suggest that the ferromagnetically ordered layer of the Fe film is located at the Fe/Co interface, owning to the spin polarization or alloying of the Fe film with the ferromagnetic Co. 16 On the other hand, photoemission dichroism experiment shows that the ferromagnetically ordered layer is at the surface of the Fe film with nonferromagnetic layers underneath. 17 This contradiction promoted a number of studies recently on the ferromagnetically ordered layer in the Fe/Co/Cu(100) and Fe/Ni/Cu(100) systems. By measuring the magnetic remanence and its temperature dependence in Fe/Ni/Cu(100) using magneto-optic Kerr effect (MOKE), Schirmer and Wuttig suggest that the fcc/Fe film is ferromagnetically ordered both at the surface and at the Fe/Ni interface in the 5-11 ML thickness range. 18 With magnetic dichroism measurement, Dallmeyer et al. observed an oscillatory behavior of the Fe magnetic signal in Fe/Co/ Cu(100) and Co/Fe/Co/Cu(100) systems, suggesting a complicated antiferromagnetic structure of the fcc/Fe in the 5-11 ML thickness range. ¹⁹ A more detailed study on Fe/Ni bilayers on Cu(100) using MOKE provides further evidence at the interfacial ferromagnetically ordered layer of the fcc Fe film.²⁰

In most of the previous studies, information on the ferromagnetically ordered layer was obtained indirectly by analyzing the macroscopic magnetic remanence. There is a lack of direct information on the Fe interfacial magnetism in comparison with the ferromagnetic Co or Ni layers at the interface. In this paper, we report results of a study of the Ni/Fe/Co/Cu(100) system using photoemission electron microscope (PEEM). With element specific domain imaging, we show strong evidence that the Fe layers at both the Fe/Co and Fe/Ni interfaces are ferromagnetically ordered in 4–12

ML thickness range due to the direct spin polarization of the Co and Ni layers. The magnetic order of the ferromagnetically ordered layer at the Fe/Ni interface disappears once the temperature exceeds the Curie temperature of the Ni layer. Moreover, the oscillatory interlayer coupling between Co and Ni results in an oscillation of the Ni layer Curie temperature.

II. EXPERIMENT

A \sim 2 mm thick Cu(100) single crystal disk of 10 mm diameter was mechanically polished using 0.25 μm diamond paste and finished with electropolishing. After ultrasonic cleaning in acetone, the Cu crystal was introduced into an ultrahigh vacuum (UHV) system of a base pressure of ~3 $\times 10^{-10}$ Torr. The Cu crystal was further cleaned in the UHV chamber by cycles of Ar-ion sputtering at 2-5 keV and annealing at ~600 °C. LEED, reflection high-energy electron diffraction (RHEED), and Auger electron spectroscopy were applied to characterize the substrate. Co, Fe, and Ni were evaporated from alumna crucibles heated with tungsten wires onto the Cu(100) held at room temperature. The growth rate (∼1 ML/min) was measured with a quartz oscillator that was calibrated by RHEED oscillations. A 10 ML fcc Co film was first grown on the Cu(100), followed by the Fe and Ni layers. The Fe and Ni films were grown into crossed wedges so that their thicknesses can be varied independently. The pressure during the film growth remained below 8×10^{-10} Torr. Details on the sample preparation using this UHV system were reported in an earlier paper. 15 After the Ni/Fe/Co/Cu(100) sample growth, another 11 ML Cu was grown on top of the Ni to protect the sample from contamination.

The sample was then brought to the Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory, and was transferred into the PEEM chamber at beamline 7.3.1. A spherical grating monochromator deferromagnetically ordered monochromatic radiation in the energy range of 170-1500 eV, which covers the 2p levels of most of the transition metals. The sample is placed in the monochromatic focal plane of the incident x-ray. A mask upstream from the monochromator is used to select above plane (left circularly polarized) radiation. The 1.2 m long elliptical refocusing mirror reduces the horizontal source size of 300 μ m (full width at half maximum FWHM) to an image size of $\sim 30 \mu m$ (FWHM), while accepting 2.0 mrad from the source in the horizontal direction. The photon flux is ~ 3 $\times 10^{12}$ photons in a 30 μ m spot when the storage ring is operated at 1.9 GeV with a ring current of 400 mA. The resolving power of the beamline is $E/\Delta E = 1800$. The x-ray incident beam makes an angle of 60° from the sample surface normal direction. The starting positions of the Fe and Ni wedges were determined using the respective 2p core levels, and magnetic domain images were constructed by taking the ratio of images acquired at the L_3 and L_2 edges utilizing the effect of x-ray magnetic circular dichroism (XMCD). All domain images in this paper have the size of $35 \times 35 \mu m$. Details on the principle and operation of this PEEM can be found in an earlier paper.²¹

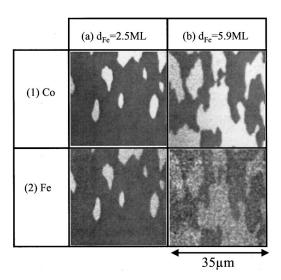


FIG. 1. Co and Fe magnetic domains of Cu(11 ML)/Fe/Co(10 ML)/Cu(100). The rows represent (1) Co and (2) Fe domains, and the columns are for (a) $d_{\rm Fe}$ = 2.5 ML and (b) $d_{\rm Fe}$ = 5.9 ML.

III. RESULTS AND DISCUSSION

1. Cu(11 ML)/Fe/Co(10 ML)/Cu(100)

We first studied the magnetic domains as a function of the Fe film thickness ($d_{\rm Fe}$) without the top Ni layer. The measurements were taken at the room temperature. Figure 1 shows the magnetic domains of Co and Fe film with different Fe thickness. Throughout the thickness range studied, we observed magnetic domains in both Co and Fe films, and also found that the domain patterns of the Fe films are identical to that of Co. The magnetization of Fe/Co/Cu(001) should be in plane as measured by SMOKE. ¹⁵ The result shows that magnetic ordering temperature of the Fe films on Co is higher than room temperature, in agreement with the earlier results. ^{14,15} In particular, the appearance of the Fe magnetic domains in the 4–12 ML region proves the existence of the ferromagnetically ordered layer at room temperature.

Figure 2 shows the asymmetry of the x-ray magnetic circular dichroism signal versus the Fe film thickness. The XMCD asymmetry was calculated using intensities from the white and dark areas of the magnetic domains.

$$I_A = \frac{I_{\text{white}} - I_{\text{dark}}}{I_{\text{white}} + I_{\text{dark}}}.$$
 (1)

The XMCD asymmetries of both the L_3 and L_2 edges were calculated and were added together as the final asymmetry. The background signals, determined from the intensities at 15 eV below the L_3 edge and 15 eV above the L_2 edge, were subtracted from the L_3 and L_2 intensities. As a comparison, the I_A value from the 10 ML Co is also shown in Fig. 2. The constant I_A value of Co shows that the Fe thickness variation has no effect on the Co magnetic dichroism signal. For the Fe signal, the value of I_A is higher below 4 ML of Fe due to the ferromagnetic phase in this thickness regime. Between 4 and 12 ML, the value of I_A is significantly lower due to the formation of the antiferromagnetic phase, and this reduced

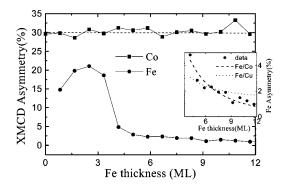


FIG. 2. XMCD asymmetry of the Co and Fe films in Cu(11 ML)/Fe/Co(10 ML)/Cu(100) as a function of the Fe film thickness. The dashed line is the guide to eyes. The inset is the zoom in of the Fe data in the 4–12 ML thickness range. The dotted and dashed lines in the inset are the fitting results with the ferromagnetically ordered layer located at the Fe/Cu and Fe/Co interfaces, respectively (see text). The better fit of the dashed line suggests that the ferromagnetically ordered layer is at the Fe/Co interface.

signal is from the ferromagnetically ordered layer in this thickness range. 14,15 Moreover, the Fe asymmetry decays with the Fe film thickness in the 4–12 ML regime. To understand this thickness dependent behavior, we need a quantitative understanding of the magnetic dichroism signal.

To do the analysis, it is important to note that PEEM measures the intensity of secondary electrons that have a finite attenuation distance. Figure 3 shows the averaged L_3 edge intensities of the Co and Fe as a function of the Fe film thickness (a background signal has been subtracted). With an exponential dependence of the secondary electron emission intensity, it is easy to show that the L_3 edge intensities of the $\operatorname{Co}(I_{\operatorname{Co}})$ and $\operatorname{Fe}(I_{\operatorname{Fe}})$ should depend on the Fe film thickness d_{Fe} as

$$I_{\text{Co}} = I_{\text{Co}}^{0} \exp(-d_{\text{Fe}}/\lambda_{\text{Co}}),$$
 (2)
 $I_{\text{Fe}} = I_{\text{Fe}}^{\infty} [1 - \exp(-d_{\text{Fe}}/\lambda_{\text{Fe}})].$

Here I_{Co}^0 is the Co signal without Fe layer, and I_{Fe}^∞ is the Fe signal when the Fe thickness is infinite. λ is a phenomenological parameter that results from the secondary electron escape depth λ_e and the x-ray penetration depth λ_x . When considering the x-ray saturation effect, it was shown that λ should be a combination of λ_e and λ_x in a way of $1/\lambda$

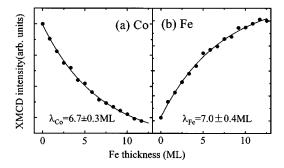


FIG. 3. The L_3 edge intensities of (a) Co and (b) Fe versus the Fe film thickness. The solid lines are the fitting results of Eq. (2).

= $1/\lambda_e + 1/\lambda_x \cos \theta$, where θ is the x-ray incident angle.²² Away from the resonance, $\lambda_x \gg \lambda_e$ so that $\lambda \approx \lambda_e$. Thus λ_{Co} in Eq. (2) should depict the electron escape depth because x-ray absorption by the Fe layer is negligible at the Co resonance peak. However, λ_{Fe} in Eq. (2) should be a combination of electron escape depth and the x-ray penetration depth. Using Eq. (2), we fitted the Co and Fe intensities (solid lines in Fig. 3) and deduced the values of $\lambda_{Co} = 6.7 \pm 0.3$ ML and $\lambda_{Fe} = 7.0 \pm 0.4$ ML. The close value of λ_{Co} and λ_{Fe} indicates that the x-ray saturation effect is insignificant in the thickness range studied. Nevertheless, we will only treat λ as a phenomenological parameter in later discussions.

The asymmetry of the 10 ML Co is not influenced by this depth attenuation because the whole Co layer is ferromagnetic so that both $I_{\rm white}$ and $I_{\rm dark}$ decay in the same way. For the ferromagnetically ordered layer of the Fe film, however, the attenuation will have a significant effect on the asymmetry because only the *ferromagnetic* part of the Fe film contributes to $I_{\rm white}-I_{\rm dark}$ while the both the *ferromagnetic* and the *nonferromagnetic* parts contribute to $I_{\rm white}+I_{\rm dark}$. Let I_{A0} , $d_{\rm FM}$, and $z_{\rm FM}$ denote the asymmetry, the thickness, and the position of the ferromagnetically ordered layer (e.g., $z_{\rm FM}=0$ or $d_{\rm Fe}$ corresponds to the ferromagnetically ordered layer at the Fe/Cu or Fe/Co interface, respectively). Then the asymmetry of the Fe in the ferromagnetically ordered layer regime should be

$$I_{A} = I_{A0} \frac{\int_{\text{FM}} \exp(-z/\lambda) dz}{\int_{\text{Whole}} \exp(-z/\lambda) dz} = I_{A0} \frac{d_{\text{FM}} \exp(-z_{\text{FM}}/\lambda)}{\lambda \left[1 - \exp(-d_{\text{Fe}}/\lambda)\right]}.$$
(3)

Here we have assumed $d_{\text{FM}} \leq \lambda$. Equation (3) shows that the thickness dependence of the Fe asymmetry depends on the location of the ferromagnetically ordered layer. The statistics of our experimental data is not good enough to determine the value of z_{FM} precisely, but it is good enough to distinguish between the Fe/Cu interfacial ferromagnetically ordered layer case ($z_{\rm FM}$ =0) and the Fe/Co interfacial ferromagnetically ordered layer case ($z_{\rm FM} = d_{\rm Fe}$). The dashed and dotted lines in the inset of Fig. 2 are the fitting results using Eq. (3) with $z_{\text{FM}} = 0$ and $z_{\text{FM}} = d_{\text{Fe}}$, respectively. Obviously, the $z_{\rm FM} = d_{\rm Fe}$ fits the experimental data better. Therefore the case of a ferromagnetically ordered layer at the Fe/Co interface agrees better with the experiment data than the case of a ferromagnetically ordered layer at the Fe/Cu interface. We believe that the ferromagnetically ordered layer is a result of the direct spin polarization from the ferromagnetic Co. From the fitting, we can also deduce the value of $I_{A0}d_{\rm FM}$. We found that the $I_{A0}d_{\rm FM}$ equals roughly the value of one monolayer asymmetry in the ferromagnetic phase ($d_{\rm Fe}$ <4 ML). In other words, if the magnetic moment of the ferromagnetically ordered layer has the same magnitude as that in the ferromagnetic phase ($d_{\rm Fe}$ <4 ML), the ferromagnetically ordered layer consists only one atomic layer $d_{\rm FM} \approx 1$ ML.

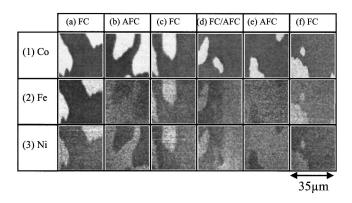


FIG. 4. Co, Ni, and Fe magnetic domains from Cu(11 ML)/Ni(4.7 ML)/Fe/Co(10 ML)/Cu(100). The rows represent (1) Co, (2) Fe, and (3) Ni, and the columns are for (a) $d_{\rm Fe}$ = 2.2 ML, (b) $d_{\rm Fe}$ = 4.8 ML, (c) $d_{\rm Fe}$ = 8.1 ML, (d) $d_{\rm Fe}$ = 9.9 ML, (e) $d_{\rm Fe}$ = 11.4 ML, and (f) $d_{\rm Fe}$ = 14.0 ML.

2. Cu(11 ML)/Ni(4.7 ML)/Fe/Co(10 ML)/Cu(100)

With the Ni layer on top of the Fe, we acquired domain images of the Ni, Fe, and Co as a function of the Fe film thickness (Fig. 4). The Ni magnetization is in the plane of the film below 8 ML because the Fe/Ni interfacial magnetic anisotropy favors in-plane magnetization.²⁰ Below 4 ML of Fe, the domain patterns of the Ni, Fe, and Co films are identical, which is not surprising because the Fe film is ferromagnetic so that all these three layers should be coupled ferromagnetically. Between 4 and 12 ML of the Fe, the Ni and Co domain patterns have the same shape but their corresponding colors (white or dark) alternate with the Fe film thickness. For example, the Ni and Co domains have the opposite colors at $d_{\rm Fe}$ =4.8 ML but the same color at $d_{\rm Fe}$ =8.1 ML, indicating the antiparallel and the parallel alignment of the Ni and Co magnetizations, respectively. This result clearly reveals the oscillatory magnetic interlayer coupling between the Ni and Co films across the Fe layer. The separation between the two antiferromagnetic coupling peaks is ~6 ML of Fe, which is very close to the value of the long-periodicity observed in other transition-metal spacer layers. 23 The transition between the ferromagnetic coupling (FC) and the antiferromagnetic coupling (AFC) is very sharp as shown in Fig. 4(3d). Moreover, the magnitude of the Co and Ni asymmetry remains unchanged, showing that the Co and Ni magnetization directions do not rotate within the film plane (except within the domain boundary) as the Fe film thickness increases. Therefore, the Co and Ni magnetizations should have a collinear alignment.

We now turn our attention to the Fe magnetic domains (Fig. 4). Similar to the domain images of the Cu/Fe/Co/Cu(100), the Fe domain contrast is much greater below 4 ML due to the ferromagnetic phase. Between 4–12 ML the Fe domain color and contrast exhibit very interesting behavior as a function of the interlayer coupling. For FC where the Ni and Co domains have the same color, the Fe domain follows their color. For AFC where the Ni and Co have opposite colors, the Fe domain follows the color of Ni as opposed to the color of Co and also exhibits weaker contrast than the FC case. This new behavior, as compared with that in the Fe/Co/

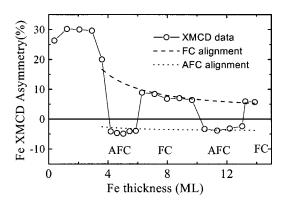


FIG. 5. Magnetic asymmetry of the films in Cu(11 ML)/Ni(4.7 ML)/Fe/Co(10 ML)/Cu(100) as a function of the Fe film thickness. Negative sign means an opposite domain color of the Fe film with respect to the Co film. The dashed and dotted lines are the fitting results (see text).

Cu(100), is obviously caused by the Ni layer on top of the Fe film. Since the Fe at the Fe/Co interface is ferromagnetically ordered due to the polarization of the Co and its magnetization is parallel to that of Co, the opposite colors of the Fe and Co domains in the AFC region suggest that the Ni top layer induces additional Fe magnetic moment with its direction parallel to that of Ni (antiparallel to that of Co). In the FC region, the Fe domain contrast is greater than that of the Fe/Co/Cu(100), also suggesting that the Ni top layer induces additional Fe magnetic moment in the same direction as that of the Ni magnetization. Therefore, we conclude that in addition to the Fe/Co interfacial ferromagnetically ordered layer, the Ni top layer also induces Fe magnetic moment in the direction of the Ni magnetization in the 4-12 ML Fe thickness range. We believe that this additional moment is located at the Fe/Ni interface due to the Ni spin polarization, the same as the ferromagnetically ordered layer at the Fe/Co interface. Then it is easy to understand qualitatively the contrast change of the Fe domains as a function of the interlayer coupling: the two interfacial ferromagnetically ordered layers at the Fe/Ni and Fe/Co interfaces add or subtract for the FC or AFC case resulting in the stronger and weaker magnetic contrasts of the Fe domains. Then the interesting question is why the Fe domain contrast does not vanish in the AFC region, but instead follows the color of the Ni domains? The residual Fe signal in the AFC region could be due to a greater Fe moment at the Fe/Ni interface than at the Fe/Co interface, but we think this is unlikely because Co has a greater magnetic moment and a higher T_C than Ni. An alternative explanation is that the Fe magnetic moments at the Fe/Ni and Fe/Co interfaces have the same magnitude but contribute differently to the domain contrast due to the finite attenuation distance of the secondary electrons. To perform a quantitative analysis, we analyzed the Fe XMCD asymmetry as a function of the Fe film thickness (Fig. 5) with the sign defined by the Co signal, i.e., the positive and negative values in Fig. 5 represent the same and opposite colors of the Fe and Co domains in the FC and AFC regions, respectively. If we assume that the Fe film at both Fe/Ni and Fe/Co interfaces have 1 ML ferromagnetically ordered layer, we can calculate the total Fe asymmetry by applying Eq. (3) at both Fe/Ni and Fe/Co interfaces.

$$I_{A} = I_{\text{Fe/Co}} + I_{\text{Fe/Ni}}$$

$$= \frac{d_{\text{FM}} [I_{0}^{\text{Fe/Co}} \exp(-d_{\text{Fe}}/\lambda) + I_{0}^{\text{Fe/Ni}}]}{\lambda [1 - \exp(-d_{\text{Fe}}/\lambda)]} \quad \text{for FC,} \quad (4)$$

$$I_{A} = I_{\text{Fe/Co}} - I_{\text{Fe/Ni}}$$

$$= \frac{d_{\text{FM}} [I_{0}^{\text{Fe/Co}} \exp(-d_{\text{Fe}}/\lambda) - I_{0}^{\text{Fe/Ni}}]}{\lambda [1 - \exp(-d_{\text{Fe}}/\lambda)]} \quad \text{for AFC.} \quad (5)$$

The values of $I_0^{\rm Fe/Co}$ and $I_0^{\rm Fe/Ni}$ were assumed to be different to take into account the possible different Fe magnetic moments at these two interfaces. From Fig. 2, $I_0^{\rm Fe/Co}$ was determined to be the same as 1 ML ferromagnetic Fe signal, then the total Fe asymmetry for the FC and the AFC can be fitted using Eqs. (4) and (5) with $I_0^{\rm Fe/Ni}$ as a fitting parameter. The fitting result (Fig. 5) agrees reasonably well to the experimental data. The value of $I_0^{\rm Fe/Ni}$ was found to be ~81% of $I_0^{\rm Fe/Co}$. The lower value of $I_0^{\rm Fe/Ni}$ could be due to a weaker Fe magnetic moment at the Fe/Ni interface, or due to the Curie temperature effect (see following section).

3. Magnetic order of the Fe layer at the Fe/Ni interface

To further confirm the Fe interfacial ferromagnetically ordered layer, we studied the magnetic domains with different Ni magnetic states. If the Fe ferromagnetically ordered layer is due to the direct spin polarization of the ferromagnetic layer, the loss of the Ni ferromagnetic order will trigger the loss of the magnetic order of the Fe layer at the Fe/Ni interface, leaving only the ferromagnetically ordered layer at the Fe/Co interface. From the preceding section, we know that when the Ni and Co layers are antiferromagnetically coupled, the magnetizations of the Fe layers at the Fe/Ni and Fe/Co interfaces are aligned antiparallel and the net color of the Fe domains follows that of Ni due to the effect of the electron escape depth. If the magnetic order of the Fe layer at the Fe/Ni interface disappears together with the magnetic order of Ni layer, the Fe domains will only come from the layer at the Fe/Co interface so that the Fe domains should switch its color from the color of Ni to the color of Co. Therefore, a study of the Fe domain color below and above the Curie temperature (T_C) of the Ni layer should further identify the interfacial nature of the ferromagnetically ordered layer. There are two ways to destroy the ferromagnetic order of the Ni layer: reducing the Ni thickness or increasing the sample temperature. We performed both experiments.

We first discuss the results obtained by varying the Ni thickness at room temperature. Figure 6 shows the Co, Ni, and Fe magnetic domains at different Ni thickness. The Fe film thickness ($d_{\rm Fe}$ =5.0 ML) was chosen to produce AFC between the Ni and the Co layers. For thicker Ni, magnetic order exists in the Ni layer as evidenced by the Ni magnetic domains [Fig. 6(3a)]. The Fe magnetic domains [Fig. 6(2a)] in this situation follow the color of Ni (opposite to the color of Co). For thinner Ni, the magnetic domains of the Ni layer vanish [Fig. 6(3c)], showing that the Ni layer loses its mag-

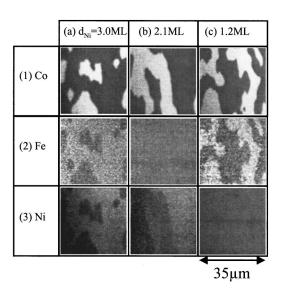


FIG. 6. Magnetic domains of (1) Co, (2) Fe, and (3) Ni from Cu(11 ML)/Ni/Fe(5.0 ML)/Co(10 ML)/Cu(100) at different Ni thickness of (a) 3.0, (b) 2.1, and (c) 1.2 ML.

netic order, i.e., the T_C of the Ni layer at this thickness is below the room temperature. The Fe film in this situation changes its domain color to follow the color of the Co film [Fig. 6(2c)], confirming our speculation that the Fe signal in this situation should come from the Fe layer at Fe/Co interface. In addition, the greater contrast in Fig. 6(2c) than in Fig. 6(2a) also supports the assumption of the magnetically ordered interfacial layer, because the signal in Fig. 6(2c) comes from the Fe/Co interface only, while the signal in Fig. 6(2a) comes from Fe/Ni and Fe/Co interfaces whose magnetizations are antiparallely aligned. Before the Ni layer loses its magnetic order with decreasing its film thickness, the weakened Ni magnetic moment also decreases the Fe layer magnetization at the Fe/Ni interface. Then at a critical Ni thickness, the Fe XMCD signal from the Fe/Ni interface should just balance out the Fe XMCD signal from the Fe/Co interface to result in a zero contrast of the Fe domains. This phenomenon was indeed observed in the experiment where we observed both Co and Ni domains [Figs. 6(1b) and 6(3b)] but not the Fe domains [Fig. 6(2b)].

We also did the experiment on the same location of the sample (d_{Ni} =3.1 ML and d_{Fe} =4.9 ML) by varying the temperature of the film. Again the Fe film thickness was chosen to produce the AFC between the Ni and Co layers. At room temperature, both Ni and Co magnetic domains exist with opposite colors [Figs. 7(1a) and 7(3a)] and the Fe magnetic domains [Fig. 7(2a)] follow the color of Ni (opposite to the color of Co). As the temperature increases to 110 °C, the Ni domain contrast is weakened due to the decrease of its magnetization. The Fe image at this temperature completely loses its domain contrast [Fig. 7(2b)], showing the balance of the Fe XMCD signals from the Fe/Ni and Fe/Co interfaces. As the temperature increases further to 160 °C, the magnetic domains of the Ni layer vanish [Fig. 7(3c)], showing that the temperature is higher than T_C of the Ni layer. The Fe magnetic domains appear at this temperature [Fig. 7(2c)] but changed their color to that of the Co film. When the sample

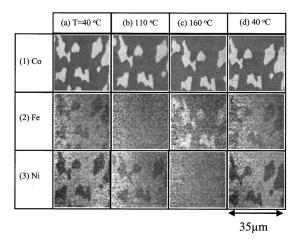


FIG. 7. Magnetic domains of (1) Co, (2) Fe, and (3) Ni from Cu(11 ML)/Ni(3.1 ML)/Fe(4.9 ML)/Co(10 ML)/Cu(100) at different temperatures of (a) 40 °C, (b) 110 °C, (c) 160 °C, and (d) cooling back to 40 °C after heating.

is cooled back to room temperature, all Co, Fe, and Ni domains recover their original shapes and colors [Figs. 7(1d), 7(2d), and 7(3d)]. This temperature dependent experiment further supports our speculation that the Fe at both Fe/Ni and Fe/Co interfaces are ferromagnetically ordered and the Fe ferromagnetically ordered layer at the Fe/Ni interface loses its magnetic order together with the Ni layer.

4. Oscillations of the Ni layer Curie temperature

Long-range magnetic order in ferromagnetic thin films is an interesting topic in low-dimensional magnetism. The Curie temperature of a ferromagnetic thin film is usually lower than the corresponding bulk value due to the reduced dimensionality. For the case of Ni thin films, a recent study²⁴ shows that the T_C follows a scaling law depending on the film thickness. For coupled sandwiches, T_C oscillations were observed in Co/Cu/Ni/Cu(100) system in the 2-4.5 ML Cu thickness range.²⁵ We studied the Ni layer T_C in the Ni/Fe/ Co/Cu(100) system as a function of the Fe film thickness. Instead of measuring the T_C at fixed Ni thickness, which is very time consuming, we measured at room temperature the Ni critical thickness (d_C) at which the magnetic long-range order disappears. In this way, the dependence of the Ni layer T_C on the Fe spacer layer thickness is manifested by the dependence of the Ni layer critical thickness (d_C) on the Fe spacer layer thickness, i.e., an enhancement of the Ni layer T_C corresponding to a reduction of the Ni critical thickness. In the experiment, we define the Ni layer critical thickness (d_C) as the thickness at which the Ni magnetic domains disappear. This definition gives the thickness of a Ni film whose T_C is room temperature.

Figure 8 shows the experimental result of the Ni layer critical thickness as a function of the Fe film thickness. The d_C clearly oscillates with increasing Fe film thickness. At the boundary between FC and AFC, where the interlayer coupling between the Ni and Co is zero, the Ni critical thickness is about 2.2 ML. In the FC and AFC region, the critical thickness become thinner, indicating an enhancement of the

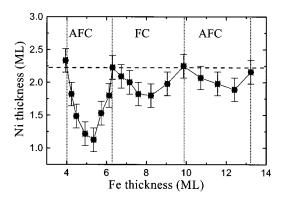


FIG. 8. The Ni critical thickness (d_C) versus the Fe film thickness. d_C is defined as the thickness at which the Ni magnetic domains lose contrast at room temperature. The vertical dashed lines show the boundaries between the AFC and FC regions. The horizontal dashed line is the guide to eyes.

Ni layer T_C due to the interlayer coupling. Therefore, the result of Fig. 8 proves the existence of the oscillatory T_C as a function of the interlayer coupling. The d_C is reduced by maximum \sim 1 ML. Recalling that the T_C of Ni film increases with film thickness at a rate of \sim 30 K/ML, 24 we estimate that T_C in our experiment is enhanced by maximum \sim 30 K.

As mentioned earlier, the T_C oscillations as a function of spacer layer thickness was already observed in Co/Cu/Ni/ Cu(100) system and was attributed to the interlayer coupling. 25 However, the T_C enhancement is negligibly small above 5 ML Cu. In another system of Cu/Fe/Cu(100), the T_C of the fcc-Fe film was also found to depend on the Cu capping layer thickness nonmonotonically, ²⁶ and this effect was explained in terms of the oscillatory character of the Ruderman-Kittel-Kasuya-Yosida exchange interaction in itinerant ferromagnets. The Fe T_C of this system oscillates rather fast with the Cu capping layer thickness, and can be either enhanced or reduced. In our work, the T_C of the Ni layer oscillates throughout the fcc Fe thickness range (5–13 ML), and is enhanced in both AFC and FC regions. It is unclear at this moment whether the T_C oscillations in our system have the same physical origin as the works in Refs. 24 and 25. For interlayer coupling, the coupling energy is usually written as $E_{\text{coupling}} = -J\bar{M}_{\text{Ni}} \cdot \bar{M}_{\text{Co}}$, where J is the interlayer coupling constant and \bar{M}_{Co} and \bar{M}_{Ni} are the magnetization vectors of Co and Ni layers. To a certain extent, the effect of the interlayer coupling can be viewed as an equivalent magnetic field $\bar{H} = -J\bar{M}_{\rm Co}$ applied to the Ni layer. A magnetic field can induce magnetization in a paramagnetic state. Thus the oscillatory interlayer coupling J is expected to result in an oscillatory T_C , and this enhancement should not depend on the sign of the coupling (FC or AFC). The $T_{\mathcal{C}}$ enhancement clue to this mechanism was implied by the Ni/ Cu/Co/Cu(100) system where the enhancement of T_C was found to scale with the interlayer coupling strength.²⁵ Then the interesting issue is why the T_C enhancement can be observed in our system up to 13 ML of the Fe spacer layer where it was observed in Ni/Cu/Co/Cu(100) system only below 5 ML of Cu. This difference could be either due to the much stronger interlayer coupling produced by the Fe than the Cu spacer layer or due to the antiferromagnetic nature of the fcc Fe. A temperature dependent measurement below the Néel temperature of the fcc Fe may help to resolve this issue. It will be a future project once the low-temperature measurement becomes available at the PEEM beamline of the ALS.

IV. CONCLUSION

Using the PEEM to do element specific domain imaging, we confirmed that there exists a ferromagnetic Fe ferromagnetically ordered layer in the 4–12 ML thickness range at the Fe/Co interface in the Cu/Fe/Co/Cu(100) system. In Cu/Ni/Fe/Co/Cu(100) system, there exists oscillatory interlayer coupling between Co and Ni layers across the Fe spacer layer. The Fe at both Fe/Co and Fe/Ni interfaces are ferro-

magnetically ordered in the 4–12 ML thickness range due to the direction spin polarization of the Co and Ni layers. The magnetic order of the layer at the Fe/Ni interface disappears once the temperature exceeds the Curie temperature of the Ni layer. The oscillatory interlayer coupling between Co and Ni layers was found to result in an oscillation of the Ni layer Curie temperature.

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¹D. Pescia, M. Stampanoni, G. L. Bona, A. Vaterlaus, R. F. Willis, and F. Meier, Phys. Rev. Lett. **58**, 2126 (1987).

²P. A. Montano, G. W. Fernando, B. R. Cooper, E. R. Moog, H. M. Naik, S. D. Bader, Y. C. Lee, Y. N. Darici, H. Min, and J. Marcano, Phys. Rev. Lett. **59**, 1041 (1987).

³ J. Thomassen, F. May, B. Feldmann, M. Wuttig, and H. Ibach, Phys. Rev. Lett. 69, 3831 (1992).

⁴D. Li, M. Freitag, J. Pearson, Z. Q. Qiu, and S. D. Bader, Phys. Rev. Lett. **72**, 3112 (1994).

⁵ V. L. Moruzzi, P. M. Marcus, K. Schwarz, and P. Mohn, Phys. Rev. B **34**, 1784 (1986).

⁶S. Müller, P. Bayer, C. Reischl, K. Heinz, B. Feldmann, H. Zillgen, and M. Wuttig, Phys. Rev. Lett. **74**, 765 (1995).

⁷ A. Biedermann, R. Tscheliessnig, and M. Schmid, Phys. Rev. Lett. **87**, 086103 (2001).

⁸D. Qian, X. F. Jin, J. Barthel, M. Klaua, and J. Kirschner, Phys. Rev. Lett. **87**, 227204 (2001).

⁹T. Kraft, P. M. Marcus, and M. Scheffler, Phys. Rev. B **49**, 11 511 (1994).

¹⁰T. Asada and S. Blügel, Phys. Rev. Lett. **79**, 507 (1997).

¹¹H. Jenniches, J. Shen, Ch. V. Mohan, S. Sundar Manoharan, J. Barthel, P. Ohresser, M. Klaua, and J. Krischner, Phys. Rev. B 59, 1196 (1999).

¹²B. Feldmann, B. Schirmer, A. Sokoll, and M. Wuttig, Phys. Rev. B 57, 1014 (1998).

¹³D. Q. Li, D. J. Keavney, J. Pearson, S. D. Bader, J. Pege, and W. Keune, Phys. Rev. B **57**, 10 044 (1998).

¹⁴W. L. O'Brien and B. Tonner, Phys. Rev. B **52**, 15 332 (1996).

¹⁵E. J. Escorcia-Aparicio, R. K. Kawakami, and Z. Q. Qiu, Phys. Rev. B **54**, 4155 (1996).

¹⁶D. Spišák and J. Hafner, Phys. Rev. B **62**, 9575 (2000).

¹⁷ X. Y. Gao, M. Salvietti, W. Kuch, C. M. Schneider, and J. Kirschner, Phys. Rev. B **58**, 15 426 (1998).

¹⁸B. Schirmer and M. Wuttig, Phys. Rev. B **60**, 12 945 (1999).

¹⁹A. Dallmeyer, K. Maiti, O. Rader, L. Pasquali, C. Carbone, and W. Eberhardt, Phys. Rev. B 63, 104413 (2001).

²⁰X. Liu and M. Wuttig, Phys. Rev. B **64**, 104408 (2001).

²¹S. Anders, H. A. Padmore, R. M. Duarte, T. Renner, T. Stammler, A. Scholl, M. R. Scheinfein, J. Stöhr, L. Séve, and B. Sinkovic, Rev. Sci. Instrum. **70**, 3973 (1999).

²²R. Nakajima, J. Stöhr, and Y. U. Idzerda, Phys. Rev. B **59**, 6421 (1999).

²³S. S. P. Parkin, Phys. Rev. Lett. **67**, 3598 (1991).

²⁴R. Zhang and R. F. Willis, Phys. Rev. Lett. **86**, 2665 (2001).

²⁵ A. Ney, F. Wilhelm, M. Farle, P. Poulopoulos, P. Srivastava, and K. Baberschke, Phys. Rev. B **59**, R3938 (1999).

²⁶R. Vollmer, S. van Dijken, M. Schleberger, and J. Kirschner, Phys. Rev. B 61, 1303 (2000).

²⁷ M. Pajda, J. Kudrnovský, I. Turek, V. Drchal, and P. Bruno, Phys. Rev. Lett. 85, 5424 (2000).